# Executive Summary

Solar system exploration is that grand human endeavor which reaches out through interplanetary space to discover the nature and origins of the system of planets in which we live and to learn whether life exists beyond Earth. It is an international enterprise involving scientists, engineers, managers, politicians, and others, sometimes working together and sometimes in competition, to open new frontiers of knowledge. It has a proud past, a productive present, and an auspicious future.

Solar system exploration is a compelling activity. It places within our grasp answers to basic questions of profound human interest: Are we alone? Where did we come from? What is our destiny? Further, it leads to the creation of knowledge that will improve the human condition. Mars and icy satellite explorations may soon provide an answer to the first of these questions. Exploration of comets, primitive asteroids, and Kuiper Belt objects may have much to say about the second. Surveys of near-Earth objects and further exploration of planetary atmospheres will show something about the third. Finally, explorations of all planetary environments will result in a much improved understanding of the natural processes that shape the world in which we live.

This survey was requested by the National Aeronautics and Space Administration (NASA) to determine the contemporary nature of solar system exploration and why it remains a compelling activity today. A broad survey of the state of knowledge was requested. In addition, NASA asked for identification of the top-level scientific questions to guide its ongoing program and a prioritized list of the most promising avenues for flight investigations and supporting ground-based activities. To accomplish this task, the Solar System Exploration Survey's (SSE Survey's) Steering Group and panels have worked with scientists, professional societies, NASA and National Science Foundation (NSF) officials, people at government and private laboratories, and members of the interested public. The remarkable breadth and diversity in the subject are evident in the panel reports that constitute Part One of this survey. Together they strongly reinforce the idea that a high-level integration of the goals, ideas, and requirements that exist in the community is essential if a practical exploration strategy for the next decade is to emerge. Such an integrated strategy is the objective of Part Two.

## CROSSCUTTING THEMES AND KEY QUESTIONS

Based on the material presented in Part One of this report, the SSE Survey identified the following four crosscutting themes that form an appropriate basis for an integrated strategy that can be realized by a series of missions to be flown over the next decade:

1. *The First Billion Years of Solar System History.* This first theme covers the formative period that features the initial accretion and development of Earth and its sibling planets, including the emergence of life on our globe. This pivotal epoch in the solar system's history is only dimly glimpsed at present.

2. *Volatiles and Organics: The Stuff of Life.* The second theme addresses the reality that life requires organic materials and volatiles, notably, liquid water. These materials originally condensed in the outer reaches of the solar nebula and were later delivered to the planets aboard organic-rich comets and asteroids.

3. *The Origin and Evolution of Habitable Worlds.* The third theme recognizes that our concept of the "habitable zone" has been overturned, and greatly broadened, by recent findings on Earth and elsewhere throughout our galaxy. Taking inventory of our planetary neighborhood will help to trace the evolutionary paths of the other planets and the eventual fate of our own.

4. *Processes: How Planetary Systems Work.* The fourth theme seeks deeper understanding of the fundamental mechanisms operating in the solar system today. Comprehending such processes—and how they apply to planetary bodies—is the keystone of planetary science. It will provide deep insight into the evolution of all the worlds within the solar system and of the multitude of planets being discovered around other stars.

Devolving from these four crosscutting themes are 12 key scientific questions. These are shown in Table ES.1, together with the names of the facilities and missions recommended as the most appropriate activities to address these questions. The priority and measurement objectives of these various projects are summarized in the next section.

## PRIORITIES FOR FLIGHT MISSIONS AND ADVANCED TECHNOLOGY

Progress on the tabulated scientific themes and key questions will require a series of spaceflights and supporting Earth-based activities. It is crucial to maintain a mix of mission sizes and complexities in order to balance available resources against potential schemes for implementation. For example, certain aspects of the key science questions can be met through focused and cost-effective Discovery missions (<$325 million), while other high-priority science issues will require larger, more capable projects, to be called New Frontiers. About once per decade, Flagship missions (>$650 million) will be necessary for sample return or comprehensive investigations of particularly worthy targets. Some future endeavors are so vast in scope or so difficult (e.g., sample return from Mars) that no single nation acting alone may be willing to allocate all of the resources necessary to accomplish them, and **the SSE Survey recommends that NASA encourage and continue to pursue cooperative programs with other nations**. Not only is the investigation of our celestial neighborhood inherently an international venture, but the U.S. Solar System Exploration program will also benefit programmatically and scientifically from such joint ventures.

Discovery missions are reserved for innovative and competitively procured projects responsive to new findings beyond the nation's long-term strategy. Such missions can satisfy many of the objectives identified in Part One by the individual panels. **Given Discovery's highly successful start, the SSE Survey endorses the continuation of this program, which relies on principal-investigator leadership and competition to obtain the greatest science return within a cost cap. A flight rate of no less than one launch every 18 months is recommended.**

Particularly critical in this strategy is the initiation of New Frontiers, a line of medium-class, principal-investigator-led missions as proposed in the President's fiscal year (FY) 2003 budget. **The SSE Survey strongly endorses the New Frontiers initiative. These spacecraft should be competitively procured and should have flights every 2 or 3 years, with the total cost capped at approximately twice that of a Discovery mission. Target selection should be guided by the list in this report.**

Experience has shown that large missions, which enable detailed, extended, and scientifically multifaceted observations, are an essential element of the mission mix. They allow the comprehensive exploration of science targets of extraordinarily high interest. Comparable past missions have included Viking, Voyager, Galileo, and Cassini-Huygens. **The SSE Survey recommends that Flagship (>$650 million) missions be developed and flown at a rate of about one per decade. In addition, for large missions of such inclusive scientific breadth, a broad cross section of the community should be involved in the early planning stages.**

TABLE ES.1 Crosscutting Themes, Key Scientific Questions, Missions, and Facilities

| Crosscutting Themes and Key Questions | Recommended New Missions and Facilities |
|---|---|
| ***The First Billion Years of Solar System History*** | |
| 1. What processes marked the initial stages of planet and satellite formation? | Comet Surface Sample Return<br>Kuiper Belt-Pluto Explorer<br>South Pole-Aitken Basin Sample Return |
| 2. How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas giant sibling, Saturn? | Jupiter Polar Orbiter with Probes |
| 3. How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth? | Kuiper Belt-Pluto Explorer<br>South Pole-Aitken Basin Sample Return |
| ***Volatiles and Organics: The Stuff of Life*** | |
| 4. What is the history of volatile compounds, especially water, across the solar system? | Comet Surface Sample Return<br>Jupiter Polar Orbiter with Probes<br>Kuiper Belt-Pluto Explorer |
| 5. What is the nature of organic material in the solar system and how has this matter evolved? | Comet Surface Sample Return<br>Cassini Extended |
| 6. What global mechanisms affect the evolution of volatiles on planetary bodies? | Venus In Situ Explorer<br>Mars Upper Atmosphere Orbiter |
| ***The Origin and Evolution of Habitable Worlds*** | |
| 7. What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in the solar system? | Europa Geophysical Explorer<br>Mars Science Laboratory<br>Mars Sample Return |
| 8. Does (or did) life exist beyond Earth? | Mars Sample Return |
| 9. Why have the terrestrial planets differed so dramatically in their evolutions? | Venus In Situ Explorer<br>Mars Science Laboratory<br>Mars Long-Lived Lander Network<br>Mars Sample Return |
| 10. What hazards do solar system objects present to Earth's biosphere? | Large Synoptic Survey Telescope |
| ***Processes: How Planetary Systems Work*** | |
| 11. How do the processes that shape the contemporary character of planetary bodies operate and interact? | Kuiper Belt-Pluto Explorer<br>South Pole-Aitken Basin Sample Return<br>Cassini Extended<br>Jupiter Polar Orbiter with Probes<br>Venus In Situ Explorer<br>Comet Surface Sample Return<br>Europa Geophysical Explorer<br>Mars Science Laboratory<br>Mars Upper Atmosphere Orbiter<br>Mars Long-Lived Lander Network<br>Mars Sample Return |
| 12. What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa? | Jupiter Polar Orbiter with Probes<br>Cassini Extended<br>Kuiper Belt-Pluto Explorer<br>Large Synoptic Survey Telescope |

NOTE: Since missions in the Discovery and Mars Scout lines might address many of these scientific topics, they are not shown, in order to maintain clarity.

Programmatic efficiencies are often gained by extending operational flights beyond their nominal lifetimes. Current candidates for continuation include Cassini, projects in the Mars Exploration Program, and several Discovery flights. **The SSE Survey supports NASA's current Senior Review process for deciding the scientific merits of a proposed mission extension and recommends that early planning be done to provide adequate funding of mission extensions, particularly Flagship missions and missions with international partners.**

Because resources are finite, the SSE Survey prioritized all new flight missions within each category along with any associated activities. To assess priorities in the selection of particular missions, it used the following criteria: scientific merit, "opportunity," and technological readiness. Scientific merit was measured by judging whether a project has the possibility of creating or changing a paradigm and whether the new knowledge that it produces will have a pivotal effect on the direction of future research, and, finally, on the SSE Survey's appraisal of how that knowledge would substantially strengthen the factual base of current understanding.

Because of wide differences in mission scope and the diverse circumstances of implementation, the SSE Survey, at NASA's request, prioritized only within three cost classes: small (<$325 million), medium ($325 million to $650 million), and large (>$650 million). Also, since the Mars Exploration Program line is already successfully established as a separate entity within NASA, its missions are prioritized separately in this report.

The recommendations from the SSE Survey's panels have been integrated with the Solar System Exploration program's overall goals and key questions in order to arrive at the flight-mission priorities listed in Table ES.2. The SSE Survey has included five New Frontiers missions in its priority list, recognizing that not all might be affordable within the constraints of the budgets available over the next decade.

## Recommended Solar System Flight Missions (non-Mars)

### *Europa Geophysical Explorer*

The Europa Geophysical Explorer (EGE), a Flagship mission, will investigate the probable subsurface ocean of Europa and its overlying ice shell as the critical first step in understanding the potential habitability of icy satellites. While orbiting Europa, EGE will employ gravity and altimetry measurements of Europa's tidal fluctuations to define the properties of any interior ocean and characterize the satellite's ice shell. Additional remote-sensing observations will examine the three-dimensional distribution of subsurface liquid water; elucidate the formation of surface features, including sites of current or recent activity; and identify and map surface composition, with emphasis on compounds of astrobiological interest. Prior to Europa-orbit insertion, EGE's instruments will scrutinize Ganymede and Callisto, moons that also may have subsurface oceans, thereby illuminating Europa's planetary and astrobiological context. Europa's thorough reconnaissance is a stepping stone toward understanding the astrobiological potential of all icy satellites and will pave the way for future landings on this intriguing object.

### *Kuiper Belt-Pluto Explorer*

The Kuiper Belt-Pluto Explorer (KBP) will be the first spacecraft dispatched for scientific measurements within this remote, entirely unexplored outer half of the solar system. KBP will fly past Pluto-Charon and continue on to do reconnaissance of several additional Kuiper Belt objects (KBOs). KBP's value increases as it observes more KBOs and investigates the diversity of their properties. This region should be home for the most primitive material in the solar system. KBP will address the prospect that KBOs have played a role in importing basic volatiles and molecular stock to the inner solar system, where habitable environments were created. The SSE Survey anticipates that the information returned from this mission might lead to a new paradigm for the origin and evolution of these objects and their significance in the evolution of objects in other parts of the solar system.

### *South Pole-Aitken Basin Sample Return*

The South Pole-Aitken Basin Sample Return (SPA-SR) mission will return samples from the Moon in order to constrain the early impact history of the inner solar system and to comprehend the nature of the Moon's upper

TABLE ES.2 Prioritized List of New Flight Missions for the Decade 2003-2013

| Priority in Cost Class | Mission Concept Name | Description |
|---|---|---|
| **SOLAR SYSTEM FLIGHT MISSIONS (non-Mars)** | | |
| *Small* (< $325 million) | | |
| 1 | Discovery missions at one launch every 18 months | Small, innovative, principal-investigator-led exploration missions |
| 2 | Cassini Extended | Orbiter mission at Saturn |
| *Medium* (< $650 million) | | |
| 1 | Kuiper Belt-Pluto Explorer | A flyby mission of several Kuiper Belt objects, including Pluto/Charon, to discover their physical nature and understand their endowment of volatiles |
| 2 | South Pole-Aitken Basin Sample Return | A mission to return samples from the solar system's deepest crater, which pierces the lunar mantle |
| 3 | Jupiter Polar Orbiter with Probes | A close-orbiting polar spacecraft equipped with various instruments and a relay for three probes that make measurements below the 100+ bar level |
| 4 | Venus In Situ Explorer | A core sample of Venus to be lifted into the atmosphere for compositional analysis; simultaneous atmospheric measurements |
| 5 | Comet Surface Sample Return | Several pieces of a comet's surface to be returned to Earth for organic analysis |
| *Large* (>$650 million) | | |
| 1 | Europa Geophysical Explorer | An orbiter of Jupiter's ice-encrusted satellite to seek the nature and depth of its ocean |
| **MARS FLIGHT MISSIONS (beyond 2005)** | | |
| *Small* (< $325 million) | | |
| 1 | Mars Scout line | A competitively selected line of Mars missions similar in concept to Discovery |
| 2 | Mars Upper Atmosphere Orbiter | A spacecraft dedicated to studies of Mars's upper atmosphere and plasma environment |
| *Medium* (< $650 million) | | |
| 1 | Mars Science Laboratory | A lander to carry out sophisticated surface observations and to validate sample return technologies |
| 2 | Mars Long-Lived Lander Network | A globally distributed suite of landers equipped to make comprehensive measurements of the planet's interior, surface, and atmosphere |
| *Large* (>$650 million) | | |
| 1 | Mars Sample Return | A program to return several samples of the Red Planet to search for life, develop chronology, and define ground truth. |

mantle. The South Pole-Aitken Basin, the largest impact structure known in the solar system, penetrates through the lunar crust. It is stratigraphically the oldest and deepest impact feature preserved on the Moon. The SPA-SR mission will help determine the nature of the differentiation of terrestrial planets and provide insight into the very early history of the Earth-Moon system. SPA-SR will also enable the development of sample acquisition, handling, and return technologies to be applied on other future missions.

*Jupiter Polar Orbiter with Probes*

The Jupiter Polar Orbiter with Probes (JPOP) mission will determine if Jupiter has a central core, a key issue that should help researchers decide between the two competing scenarios for the planet's origin. It will measure water abundance, which plays a pivotal role in understanding giant planet formation. This parameter indicates how volatiles ($H_2O$, $CH_4$, $NH_3$, and $H_2S$) were incorporated in the giant planets and, more specifically, the degree to which volatiles were transported from beyond Neptune to the inner solar system. The mission will probe the planet's deep winds to at least the 100-bar pressure level and may lead to an explanation of the extreme stability of the cloud-top weather systems. From its cloud-skimming orbit, JPOP will investigate the fine structure of the planet's magnetic field, providing information on how its internal dynamo works. Lastly, the spacecraft will repeatedly visit the hitherto-unexplored polar plasma environment, where magnetospheric currents crash into the turbulent atmosphere to generate powerful aurorae.

*Venus In Situ Explorer*

On descent, the Venus In Situ Explorer (VISE) mission will make compositional and isotopic measurements of the atmosphere and—quickly—of the surface. It will loft a core sample from Venus's hellish surface to cooler altitudes, where further geochemical and mineralogical data will be obtained. VISE will provide key measurements of the lower atmosphere and of surface-atmosphere interactions on Earth's would-be twin. The project will elucidate the history and stability of Venus's atmospheric greenhouse and its bizarre geological record. It will also advance the technologies required for the sample return from Venus expected in the following decade.

*Comet Surface Sample Return*

The Comet Surface Sample Return (CSSR) mission will collect materials from the near surface of an active comet and return them to Earth for analysis. These samples will furnish direct evidence on how cometary activity is driven. Information will be provided on the manner in which cometary materials are bound together and on how small bodies accrete at scales from microns to centimeters. By comparing materials on the nucleus against the coma's constituents, CSSR will indicate the selection effects at work. It will also inventory organic materials in comets. Finally, CSSR will yield the first clues on crystalline structure, isotopic ratios, and the physical relationships between volatiles, ice, refractory materials, and the comet's porosity. These observations will give important information about the building blocks of the planets.

*Small Missions*

Recommendations for small missions include a series of Discovery flights at the rate of at least one every 18 months and an extension to the Cassini-Huygens mission (Cassini Extended), presuming that the nominal mission is successful. Discovery missions are, by intent, not subject to long-term planning. Rather, they exist to create frequent opportunities to fly small missions addressing fundamental scientific questions and to pursue new research problems in creative and innovative ways.

## Recommended Mars Flight Missions

For Mars exploration, the SSE Survey endorses the current science-driven strategy of *seeking* (i.e., remote sensing), *in situ measurements* (science from landers), and *sampling* to understand Mars as a planet, understand its astrobiological significance, and afford unique perspectives about the origin of life on Earth. The evolution of life and planetary environments are intimately tied together. To understand the potential habitability of Mars, whether it has or has not supported life, we must understand tectonic, magmatic, and hydrologic evolution as well as geochemical cycles of biological relevance. The return of materials from known locations on Mars is essential in order to address science goals, including those of astrobiology, and to provide the opportunity for novel measurements, such as age-dating, and ultimate ground truth.

### *Mars Science Laboratory*

The Mars Science Laboratory (MSL) mission will conduct in situ investigations of a water-modified site that has been identified from orbit. It will provide ground truth for orbital interpretations and test hypotheses for the formation of geological features. The types of in situ measurements possible include atmospheric sampling, mineralogy and chemical composition, and tests for the presence of organics. The mission should either drill to get below the hostile surface environment or have substantial ranging capability. While carrying out its science mission, MSL should test and validate technology required for later sample return.

### *Mars Long-Lived Lander Network*

The Mars Long-Lived Lander Network ($ML^3N$) is a grid of science stations that will make coordinated measurements around Mars's globe for at least 1 martian year. The highest-priority objectives for network science on Mars are the determination of the planet's internal structure, including its core; the elucidation of surface and near-surface composition as well as thermal and mechanical properties; and extensive synoptic measurements of the atmosphere and weather. In addition, atmospheric gas isotopic observations (to constrain the size of currently active volatile reservoirs) and measurements of subsurface oxidizing properties and surface-atmosphere volatile exchange processes will be valuable.

### *Mars Sample Return*

Mars Sample Return (MSR) is required in order to perform definitive measurements to test for the presence of life, or for extinct life, as well as to address Mars's geochemical and thermal evolution. Further, characterization of Mars's atmosphere and now frozen hydrosphere will require highly sophisticated measurements and analytical equipment. To accomplish key science goals, samples must be returned from Mars and scrutinized in terrestrial laboratories**. For these reasons, the SSE Survey recommends that NASA begin its planning for Mars Sample Return missions so that their implementation can occur early in the decade 2013-2023**. Current studies of simplified Mars sample-return missions indicate that such missions are now within technological reach. Early on, NASA should engage prospective international partners in the planning and implementation of MSR.

### *Small Missions*

Mars Scout missions are required in order to address science areas that are not included in the core program and to respond to new discoveries derived from current and future missions. A series of such small (<$325 million) missions should be initiated within the Mars program for flights at alternating Mars launch opportunities. This program should be modeled on the Discovery program.

Mars Upper Atmosphere Orbiter (MAO) is a small mission dedicated to studies of Mars's upper atmosphere and plasma environment. This mission would provide quantitative information on the various atmospheric escape

TABLE ES.3 Recommended Technology Developments

| Category | Recommended Development |
|---|---|
| Power | **Advanced radioisotope power systems, in-space fission-reactor power source** |
| Propulsion | **Nuclear-electric propulsion, advanced ion engines, aerocapture** |
| Communication | **Ka band, optical communication**, large antenna arrays |
| Architecture | **Autonomy**, adaptability, lower mass, lower power |
| Avionics | **Advanced packaging and miniaturization**, standard operating system |
| Instrumentation | **Miniaturization**, environmental tolerance (temperature, pressure, and radiation) |
| Entry to landing | **Autonomous entry, precision landing**, and hazard avoidance |
| In situ operations | Sample gathering, handling, and analysis; drilling; instrumentation |
| Mobility | **Autonomy**; surface, aerial, and subsurface mobility; hard-to-reach access |
| Contamination | Forward-contamination avoidance |
| Earth return | **Ascent vehicles**, in-space rendezvous, and Earth-return systems |

NOTE: Bold type indicates a priority item.

fluxes, thus quantifying current escape rates and providing a basis for backward extrapolation in our attempt to understand the evolution of Mars's atmosphere.

### Technology Directions

A significant investment in advanced technology development is also needed for the recommended new and future flight missions to better succeed. Table ES.3 identifies a number of important areas in which technology development is appropriate. **The SSE Survey recommends that NASA commit to significant new investments in advanced technology so that future high-priority flight missions can succeed.**

## RESEARCH INFRASTRUCTURE

In an era of competitively selected missions for space exploration, it will continue to be necessary to improve the technical expertise and infrastructure of organizations providing the vital services that enable the planning and operation of all solar system exploration missions.

For missions to be the most productive scientifically, a level of funding must be ensured that is sufficient not only for the successful operation of the flight but also for the contemporaneous analysis of the data and the publication of scientific results. Moreover, the SSE Survey's mission priorities rest on a foundation that must be secured and buttressed. This foundation includes fundamental research, technology development, follow-on data analysis, ground-based facilities, sample-analysis programs, and education and public outreach activities.

The entire pipeline that brings data from distant spacecraft to the broad research community must be systematically improved. Insufficient downlink communications capacity through the Deep Space Network (DSN) currently restricts the return of data from all missions, as, occasionally, does the DSN's limited geographical coverage. The DSN has to be continually upgraded as new technologies become available and system demands increase.

Once data are on the ground, they must be swiftly archived in a widely accepted and usable format. The Planetary Data System (PDS) should be included as a scientific partner at the very early stages of missions; it must be sized to accomplish its future tasks. In order to utilize the returned information effectively, analysis programs ought to be in place to fund investigators immediately upon delivery of ready-to-use data to the PDS. Data-analysis programs should be merged across lines (e.g., Discovery, New Frontiers) rather than being tied to individual missions.

A healthy research and analysis (R&A) program is the most basic requirement for a successful program of flight missions. **The SSE Survey recommends an increase over the decade in the funding for fundamental research and analysis programs at a rate above inflation that parallels the increase in the number of missions, amount of data, and diversity of objects studied.** Previous National Research Council (NRC) studies have shown that after a serious decline in the early to mid-1990s, the overall funding for R&A programs in NASA's Office of Space Science climbed in recent years to approximately 20 percent of the overall flight-mission budget.[1,2] Figures supplied by NASA's Solar System Exploration program show that the corresponding value for planetary activities is currently closer to 25 percent and is projected to stay at about this level for the next several years. The SSE Survey believes that this is an appropriate allocation of resources.

NASA's Astrobiology program has appropriately become deeply interwoven into the solar system exploration research and analysis program. **The SSE Survey encourages NASA to continue the integration of astrobiology science objectives with those of other space science disciplines. Astrobiological expertise should be called upon when identifying optimal mission strategies and design requirements for flight-qualified instruments that address key questions in astrobiology and planetary science.**

Ground-based telescopes have been responsible for several major discoveries in solar system exploration during the past decade. Moreover, many flight missions are greatly enhanced as a result of extensive ground-based characterization of their targets. **The SSE Survey recommends that NASA partner equally with the National Science Foundation to design, build, and operate a survey facility, such as the Large Synoptic Survey Telescope (LSST) described in *Astronomy and Astrophysics in the New Millennium,*[3] to ensure that LSST's prime solar system objectives are accomplished. Other powerful new facilities highlighted in that report—for example, the James Webb Space Telescope (formerly the Next Generation Space Telescope)—should be designed, where appropriate, to be capable of observing moving solar system targets. In addition, NASA should continue to support ground-based observatories for planetary science, including the planetary radar capabilities at the Arecibo Observatory in Puerto Rico and the Deep Space Network's Goldstone facility in California, the Infrared Telescope Facility on Mauna Kea in Hawaii, and shares of cutting-edge telescopes such as the Keck telescopes on Mauna Kea, as long as they continue to be critical to missions and/or scientifically productive.**

In anticipation of the return of extraterrestrial samples from several ongoing and future missions, an analogue to the data pipeline must be developed for cosmic materials. **The SSE Survey recommends that well before cosmic materials are returned from planetary missions, NASA should establish a sample-analysis program to support instrument development, laboratory facilities, and the training of researchers. In addition, planetary protection requirements for missions to worlds of biological interest will require investments, as will life-detection techniques, sample quarantine facilities, and sterilization technologies. NASA's current administrative activities to develop planetary protection protocols for currently planned missions are appropriate.**

Education and public outreach activities connect solar system exploration with its ultimate customers—the tax-paying public—and as such are an extremely important component of the program. Solar system exploration captures the imagination of young and old alike. By correctly illustrating the scientific method at work and demonstrating scientific principles, the planetary science community's efforts in communicating with students and lay people can be influential in helping to improve science literacy and education. In most implementations today, planetary scientists and education specialists work hand-in-hand to derive innovative and effective activities for communicating about solar system exploration with students, teachers, and the public. Although some problems remain, this program is well managed and is on a solid foundation.

## CONCLUSIONS

For nearly 40 years, the U.S. Solar System Exploration program has led to an explosion of knowledge and awe with respect to our celestial neighborhood as ground-based telescopes and spacecraft have become much more capable while reaching out farther from Earth. We are now poised to address issues about our origins that have puzzled our forebears since civilization's beginning. Answers to profound questions about our origins and our future may be within our grasp. This survey describes an aggressive and yet rational strategy to deepen our analysis of such questions and finally resolve many long-standing mysteries during the next decade.

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